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A class V flextensional transducer: the cymbal

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Abstract

The cymbal is a miniaturized class V flextensional transducer which was developed for potential use as a shallow water sound projector. In underwater tests, the experimental fixture was found to have a pronounced effect on the performance of the transducer through modifications of the mechanical boundary conditions imposed on the device. A less restrictive setup was devised for the underwater test of a cymbal transducer and very good agreement between the calculations and the experimentally measured transmitting voltage response was then obtained. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Flextensional transducers were first developed in the 1920s and have been used as underwater transducers since the 1950s [1]. They consist of an active piezoelectric or magnetostrictive drive element and a mechanical shell structure. The shell is used as a mechanical transformer which transforms the high impedance, small extensional motion of the ceramic into low impedance, large flexural motion of the shell. According to the shape of the shell, flextensional transducers are divided into five classes [2].

Flextensional transducers generally range in size from several centimeters to several meters in length and can weigh up to hundreds of kilograms. They are commonly used in the frequency range 300–3000 Hz [3]. These transducers can operate at high hydrostatic pressures and have wide bandwidths with high power output.

A miniaturized version of the class V flextensional transducer called the 'moonie,' was developed at the Materials Research Laboratory at the Pennsylvania State University in the late 1980s [4]. Its basic structure is similar to a class V flextensional transducer, but its bonding and fabrication process is much simpler and this makes it very easy and inexpensive to mass-produce.

A second-generation moonie type transducer with a thinner cap and a slightly different shape, was also developed [5]. It was named the 'cymbal' because of the similarity in the shape of its cap to that of the musical instrument. The cymbal was originally designed as an actuator, which generates moderate force and displacement, filling the gap between bimorph and multilayer actuator. It was later developed by Tressler et al. as an underwater sound projector [6].

The moonie and cymbal transducers consist of a piezoelectric disk (poled in the thickness direction) sandwiched between two metal end-caps. The caps contain a shallow cavity on their inner surface. The cavities enable the caps to convert and amplify the small radial displacement of the disk into a much larger axial displacement normal to the surface of the caps. This contributes to a much larger acoustic pressure output than would occur in the uncapped ceramic.

The purpose of this work was to evaluate the effect of test fixtures on the performance of the cymbal transducer and to find a proper setup for underwater testing. Another goal was to model and predict the underwater performance of the cymbal transducer and compare it with experimental measurements.

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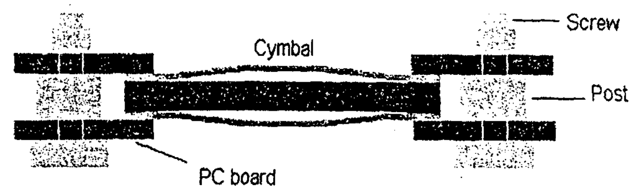
2. Experimental procedure

The piezoelectric ceramic disks (PKI402, Piezokinetics Inc., Bellefonte, PA) have a thickness of 1 mm, a diameter of 12.7 mm and were poled in the thickness direction. The silver electrodes of PZT disks were first ground with sandpaper to remove the oxide layer and then cleaned with acetone. Titanium caps were punched from Ti foil of 0.25 mm thickness and shaped using a special die. The shaped caps had a diameter of 12.7 mm. The cavity diameter was 9.0 mm at the bottom and 3.2 mm at the top. The cavity depth was 0.32 mm. The flanges of the Ti caps were ground using sandpaper. The caps were then bonded to the piezoelectric ceramic disk. The bonding material is an Emerson and Cuming insulating epoxy. A ratio of three parts 45LV epoxy resin to one part 15LV hardener was used. The thickness of the epoxy-bonding layer was approximately 20–40 μm. The entire assembly was kept under uniaxial stress in a special die for 24 h at room temperature to allow the epoxy time to cure.

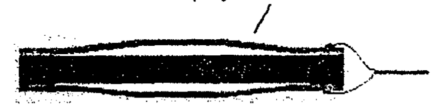
The in-air admittance was measured as a function of frequency on a Hewlett Packard 4194A impedance analyzer. Electrical leads were attached to the flange of the metal cap, taking care not to make any contact between the leads and the dome area of the metal caps.

Underwater calibration tests of single cymbals were performed at the Applied Research Laboratory at Penn State. The tank measures 5.5 m in depth, 5.3 m in width and 7.9 m in length. A pure tone sinusoidal pulse signal of 2 ms duration was applied to the test transducer and its acoustic output was monitored with a standard F33 hydrophone. The test transducer and the standard were positioned at a depth of 2.74 m and were separated by a distance of 3.16 m. The mechanical Q, transmitting voltage response (TVR), free-field voltage sensitivity (FFVS) and directivity pattern were evaluated.

In the underwater test, the cymbal transducer had to be insulated from the conductive water in the tank. In addition, it had to be rotated to observe the directivity pattern. Therefore, a fixture was needed to hold the cymbal transducer. Since we were making use of both the radial motion of the ceramic and the flextensional mode of the cap, it was difficult to test the performance of the cymbal transducer and avoid clamping effects from the fixture. Two types of fixtures were investigated for the underwater tests, as shown in Fig. 1. In the first design (PC boards, Fig. 1(a)) the cymbal transducer was sandwiched between two copper-clad PC boards each 1.5 mm thick, which also served as electrodes. A hole 11 mm in diameter was drilled through the boards. Plastic posts 1.5 mm thick were used to maintain a uniform distance between the upper and lower boards, which were then screwed tightly together to keep the transducers in place. The entire assembly was placed inside a tygon container and flooded with castor oil. This experiment was easy to set up and quite convenient to carry out.



(a) with PC boards and screws



(b) potted in polyurethane

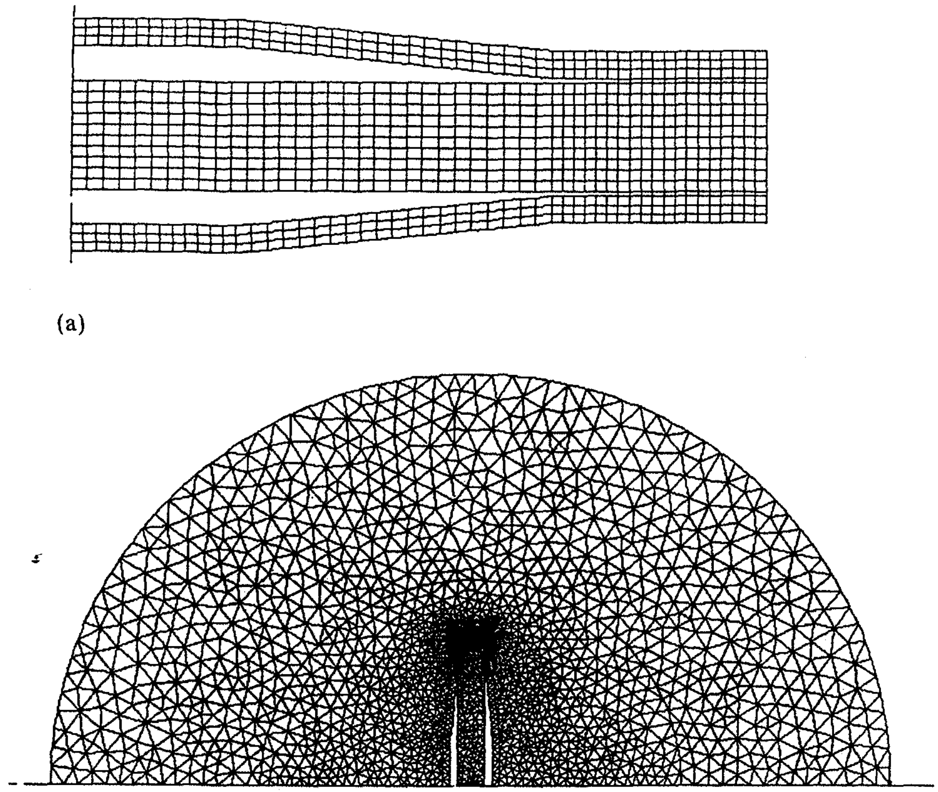
Fig. 1. Test fixtures used in the underwater tests: (a) with PC boards and screws, (b) potted in polyurethane.

In the second fixture (potted cymbal, Fig. 1(b)) a coaxial cable was first attached to the flange of the metal cap using silver epoxy. Care was taken to avoid any contact between the dome of the metal cap and the silver epoxy. The cymbal and part of the cable were then potted with a polyurethane coating about 0.5 mm thick. The polyurethane layer insulated the cymbal from the conductive water in the water tank.

3. Finite element analysis modeling

The finite element analysis code ATILA was used in modeling the performance of the cymbal transducer. ATILA was developed at the Acoustics Department at Institut Superieur d'Electronique du Nord (ISEN) to model underwater transducers and has been used successfully in the simulation of flextensional transducers [7]. Modal analysis was carried out to determine the vibration modes, their resonance and antiresonance frequencies and associated coupling factors. Through harmonic analysis, the in-air and in-water impedance and displacement field can be computed as a function of frequency, together with the TVR, FFVS and the directivity patterns.

A two dimensional axisymmetric model was used in which only half of the cymbal was meshed due to symmetry. The mechanical boundary conditions of the cymbal transducer were set free in both the in-air and the in-water modeling. The thickness of the epoxy layer was assumed to be 0.04 mm [8]. In the underwater simulation, a dipolar damping element was employed. The in-air and in-water meshes are shown in Fig. 2.



(a)

(b)

Fig. 2. Meshes of a cymbal transducer: (a) in air, (b) in water.

4. Results and discussion

Fig. 3 compares the in-air admittance spectrum of a single cymbal transducer calculated from ATILA with the experimental measurements. The calculated admittance spectrum from ATILA agreed quite well with the experimental results. The first peak corresponds to the

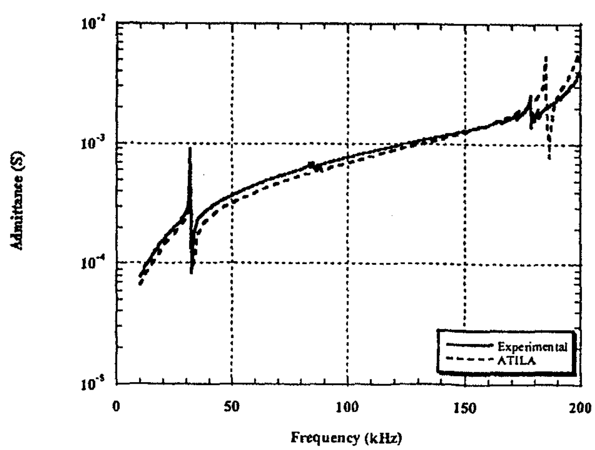


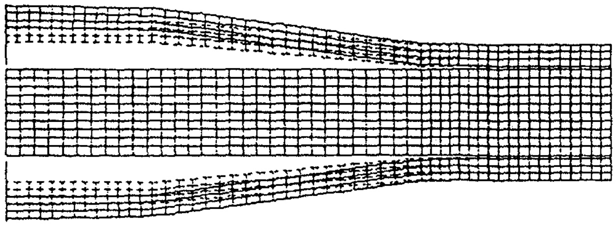
Fig. 3. Measured and calculated in-air admittance as a function of frequency for a cymbal transducer.

(0, 1) or the so-called 'umbrella' flexural mode of the metal caps. In the node notation (m, n), integer m is the number of radial node lines and integer n is the number of azimuthal nodal circles. $m=0$ for a two dimensional axisymmetric body. The second peak came from the (0, 2) mode of the metal caps. The two vibration modes are illustrated in Fig. 4. There were no other modes (peaks) between the (0, 1) and (0, 2) modes. The third peak was the (0, 3) mode of the metal caps and will not be discussed here.

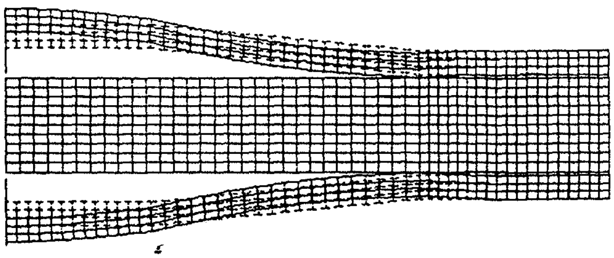
The calculated and measured in-water admittance spectra of the potted single cymbal transducer are also shown in Fig. 5. Fairly good agreement was achieved. The second peak in the admittance spectra was damped out by the water loading. The fundamental flextensional resonance frequency was shifted from 32 kHz in air down to 16 kHz in water due to the loading. For the cymbal transducer, its size is only one tenth of the wavelength at the first resonance frequency ($ka \ll 1$), so that the imaginary part of the radiation impedance (radiation reactance) can be approximated as [9]:

$$X_r = \rho c A^* 8ka/3\pi$$

where $k=\omega/c=2\pi/\lambda$, a is the radius of the cymbal, and $A=\pi a^2$.



(a) (0, 1) mode



(b) (0,2) mode

Fig. 4. Vibration modes of the cymbal transducer: (a) (0, 1) mode, (b) (0, 2) mode.

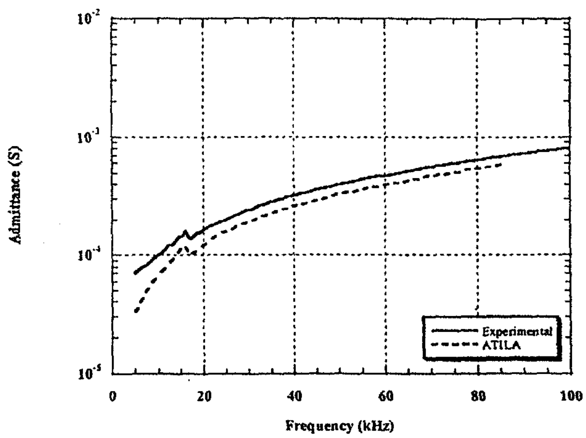


Fig. 5. Measured and calculated in-water admittance of a cymbal transducer.

The radiation reactance, X_r, can be regarded as an additional vibrating mass (M_r) given by:

$M_r = X_r/\omega = (8/3)\rho a^3$.

This mass is equivalent to that of a cylinder of water having the same cross-sectional area as the piston (cymbal) and a length of $8a/3\pi$. For a half inch cymbal transducer, the mass of the water associated with the radiation reactance is 0.7 g, which is over half the mass of the cymbal transducer itself (1.3 g). This 'associated mass' has a very significant effect on the cymbal transducer. The amplitude of the fundamental resonance

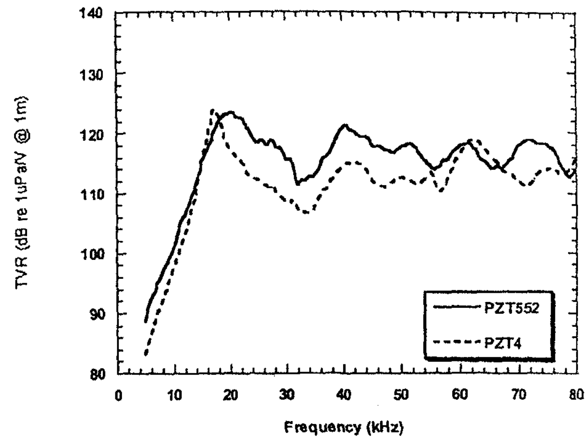


Fig. 6. Measured transmitting voltage response for a cymbal transducer of different PZT types.

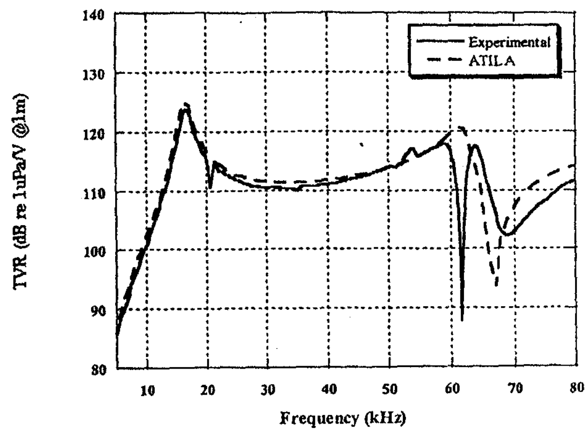


Fig. 7. Calculated and measured transmitting voltage response of a potted cymbal transducer.

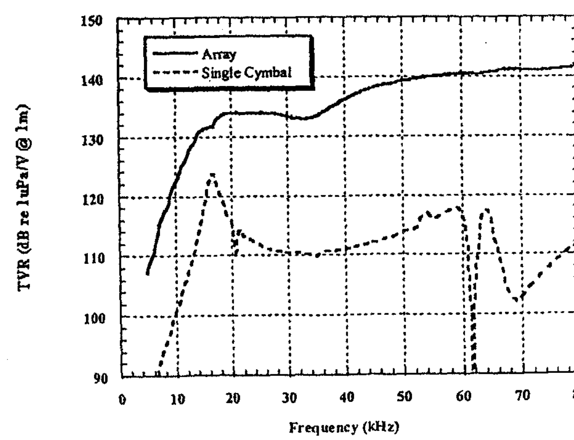


Fig. 8. Measured TVR of a potted 3 × 3 cymbal planar array.

frequency is greatly reduced, and the mechanical Q-factor was unfortunately increased.

The measured transmitting voltage response for two

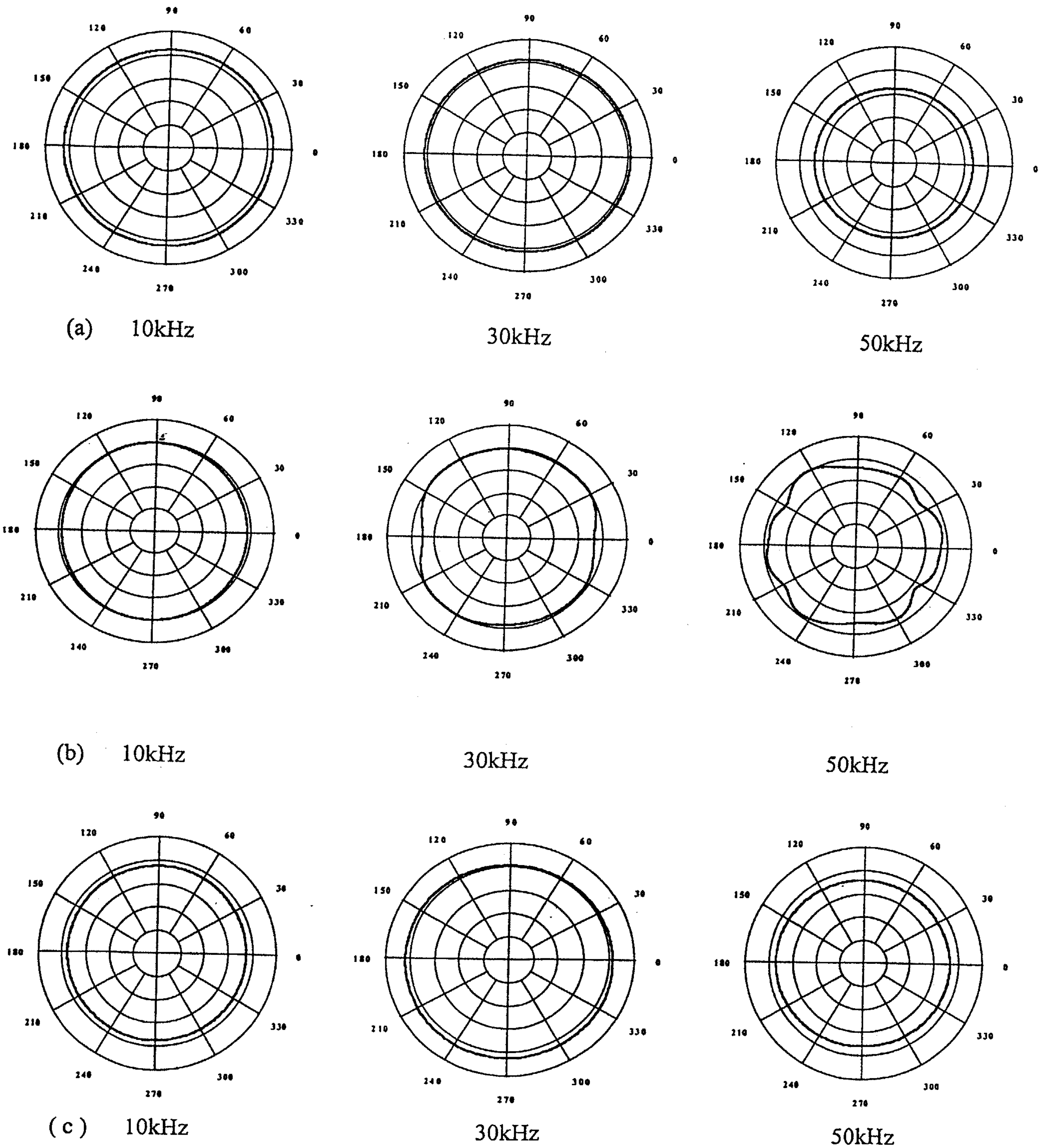


Fig. 9. Directivity patterns of a single cymbal transducer: (a) calculated from ATILA (free boundary conditions); (b) measured with PC boards (partially clamped boundary conditions); (c) measured pattern of potted sample (free boundary conditions).

single cymbals of different PZTs mounted in PC board fixtures are shown in Fig. 6. The first peak corresponds to the fundamental flextensional mode of the metal cap. After the first resonance frequency, there were several undulations in the TVR curves. The TVR patterns for different PZTs were very different, indicating that there were complex interference modes acting on the vibration of the cymbal. The calculated TVR curve from ATILA,

shown in Fig. 7, gave no peaks in this frequency range. Indeed, no peaks were expected to be in the frequency range between the (0, 1) mode and (0, 2) modes, which is apparent from the in-air admittance spectrum. We reasoned that the difference between the calculation and the measurements was related to the test fixtures which altered the mechanical boundary conditions of the cymbal transducer. In the in-air test and the FEM analysis, the boundary conditions were assumed to be 'free'. But with the PC board configuration, the small screws partially clamp the flange of the cymbal transducer. In addition, it was discovered that the PC board and the screws interfered with the vibration of the metal caps, which lead to the undulations in the TVR curves. Thus, it was difficult to predict its performance with the partially clamped boundary conditions.

A second set of test fixtures, the potted cymbal described in Section 2, was employed to minimize the clamping effect. The TVR curve of the potted cymbal transducer and the simulation are shown in Fig. 7. A nearly perfect match was obtained between them. There was a sharp dip around 65 kHz which came from the (0, 2) mode of the metal cap. As shown in the vibration mode, the two portions of the cap vibrated out of phase. The pressures from different portions of the metal caps cancelled out and lead to a sharp drop in response. There were no peaks (undulations) between the fundamental flextensional resonance frequency and the (0, 2) resonance frequency in water. The response was flat over this frequency range. This result confirms the fact that the PC board fixture plays an important role in creating the undulations observed in the previous tests.

The mechanical Q-factor is around 10 for the single cymbal transducer, which is rather high compared to other flextensional transducers. This is due to the fact that its size and weight are small, as discussed previously. Single cymbal transducers will find very limited use as sound projectors because of the high Q. But its small size and low weight and extremely low cost render possibile to incorporate it into an array to achieve the desired power and beam pattern. It has a rather flat TVR response between (0, 1) and (0, 2) modes and may be used as arrays in this frequency range. A preliminary result for a 3×3 cymbal array potted in polyurethane is shown in Fig. 8 and compared with the single cymbal transducer. The array measured 6×6 cm and had a thickness of 5 mm. A flat and much improved TVR response over the single element was observed over the frequency range of interest. Experiments are underway to design planar or conformal cymbal transducer arrays for different applications.

Directivity patterns of a single cymbal transducer tested in two types of fixtures are shown in Fig. 9 and are compared with the simulation. Near the first resonance frequency they both show omnidirectional patterns which agree with the calculation. At higher frequencies, near 30 kHz and 50 kHz, omnidirectional patterns were observed in the potted cymbal case and in the calculation. But the cymbal with the PC board fixture gave a directional pattern which deteriorates at 50 kHz. This again indicated that the test fixtures have a very pronounced effect on the performance of cymbal transducer, especially at higher frequencies, making prediction impossible. The test fixtures must be carefully chosen during the test to avoid interference with the transducer performance.

5. Conclusions

The behavior of the cymbal transducer is strongly affected by the boundary conditions imposed by the testing fixtures. Each fixture has to be properly evaluated with relation to the boundary conditions imposed on the sample and its interaction with the vibration modes of the transducer. Very good agreement between the calculated and experimentally measured transmitting voltage response and directivity patterns was obtained after the proper experimental setup was applied. ATILA can be used to predict, and therefore guide, the design of the experimental arrangements. Single cymbal transducers were characterized in underwater tests which provide valuable information that will be used in designing cymbal arrays.

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